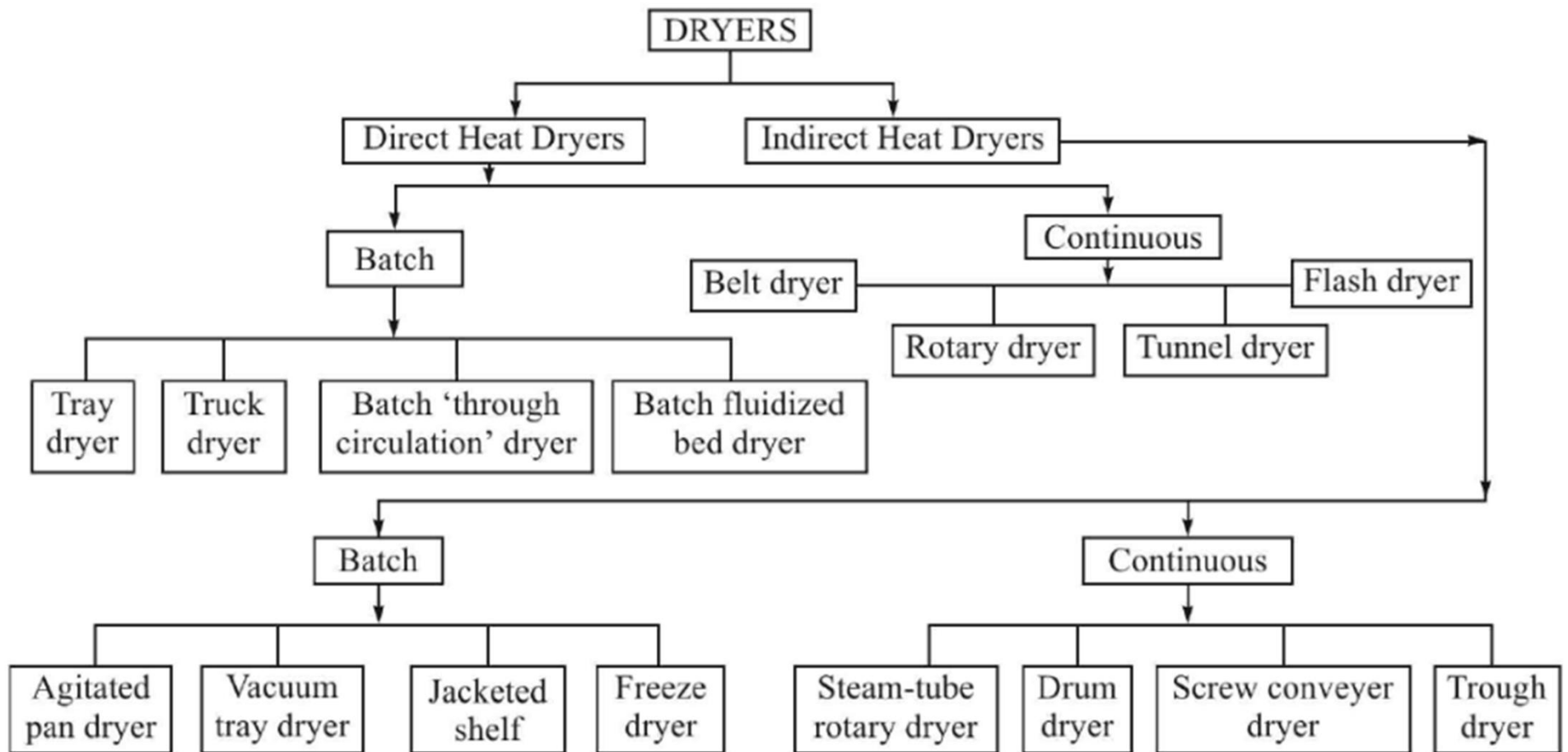
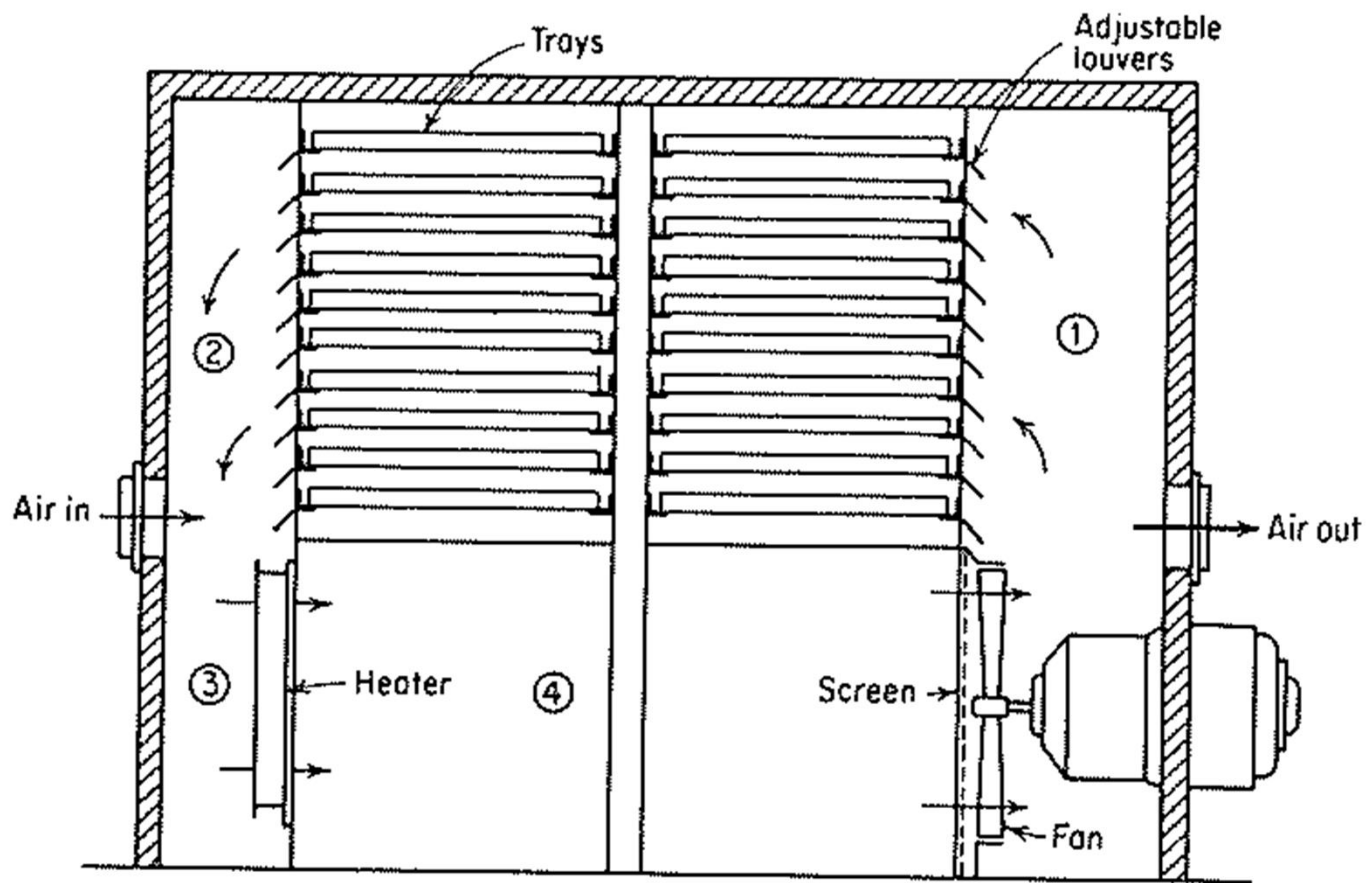


Classification of Dryers

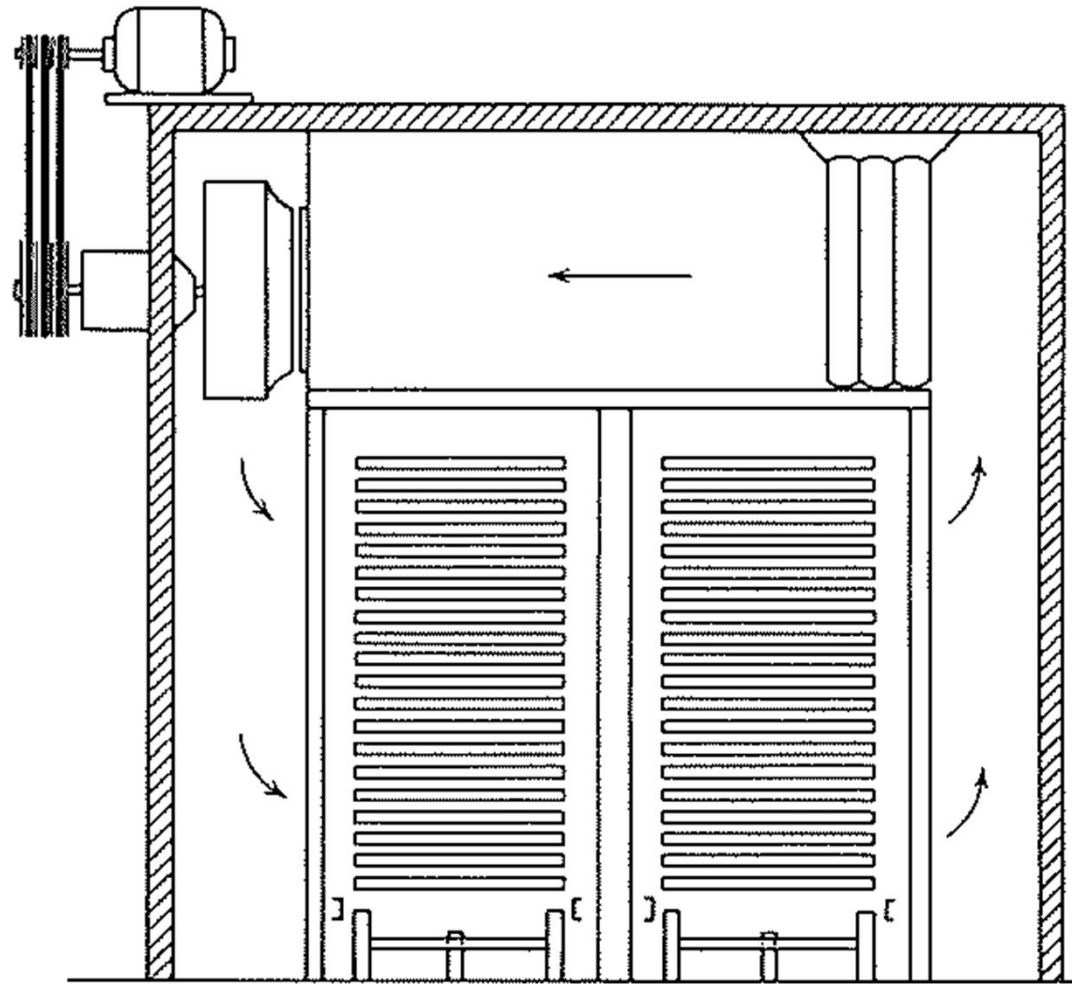


Direct driers

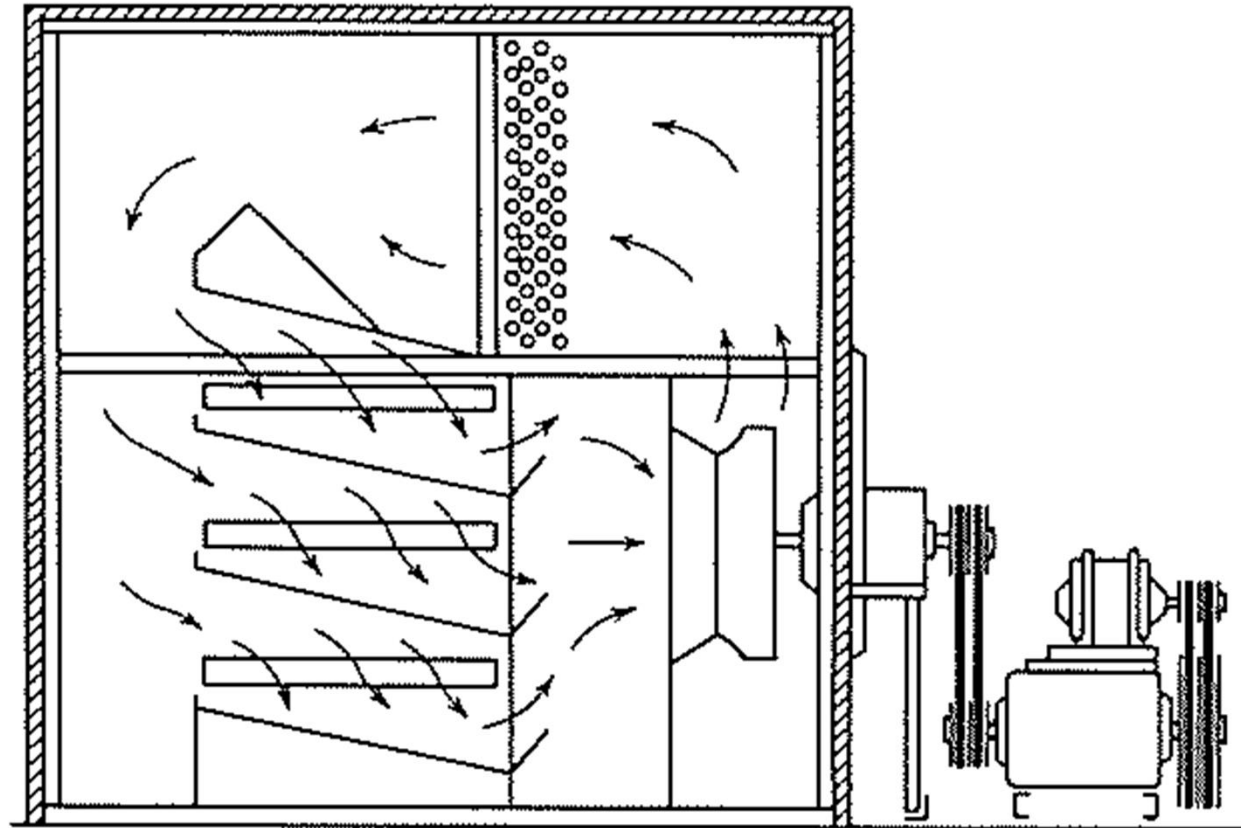
- Batch driers



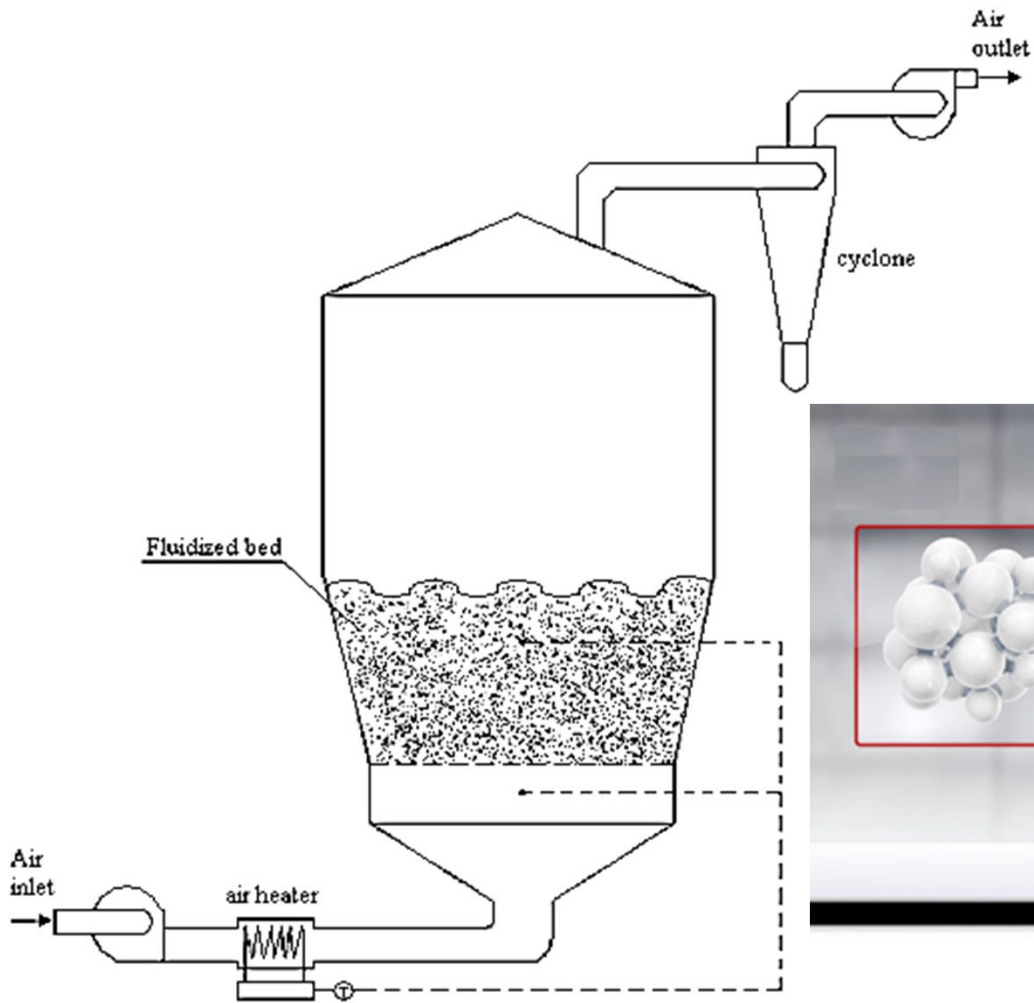
TRAY DRIER



TWO TRUCK DRIER

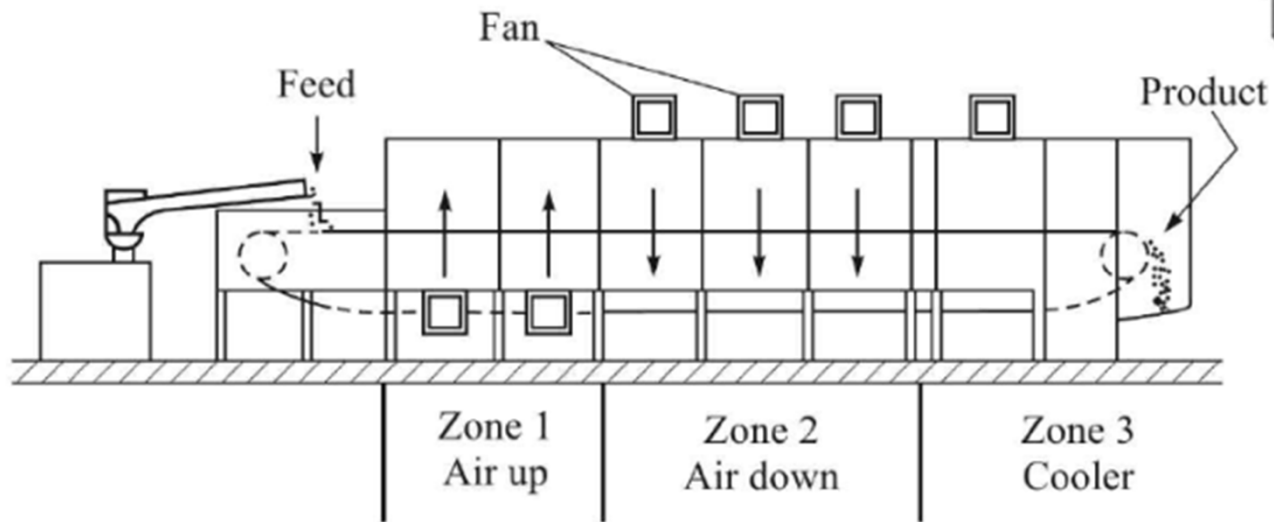


THROUGH CIRCULATION DRIER

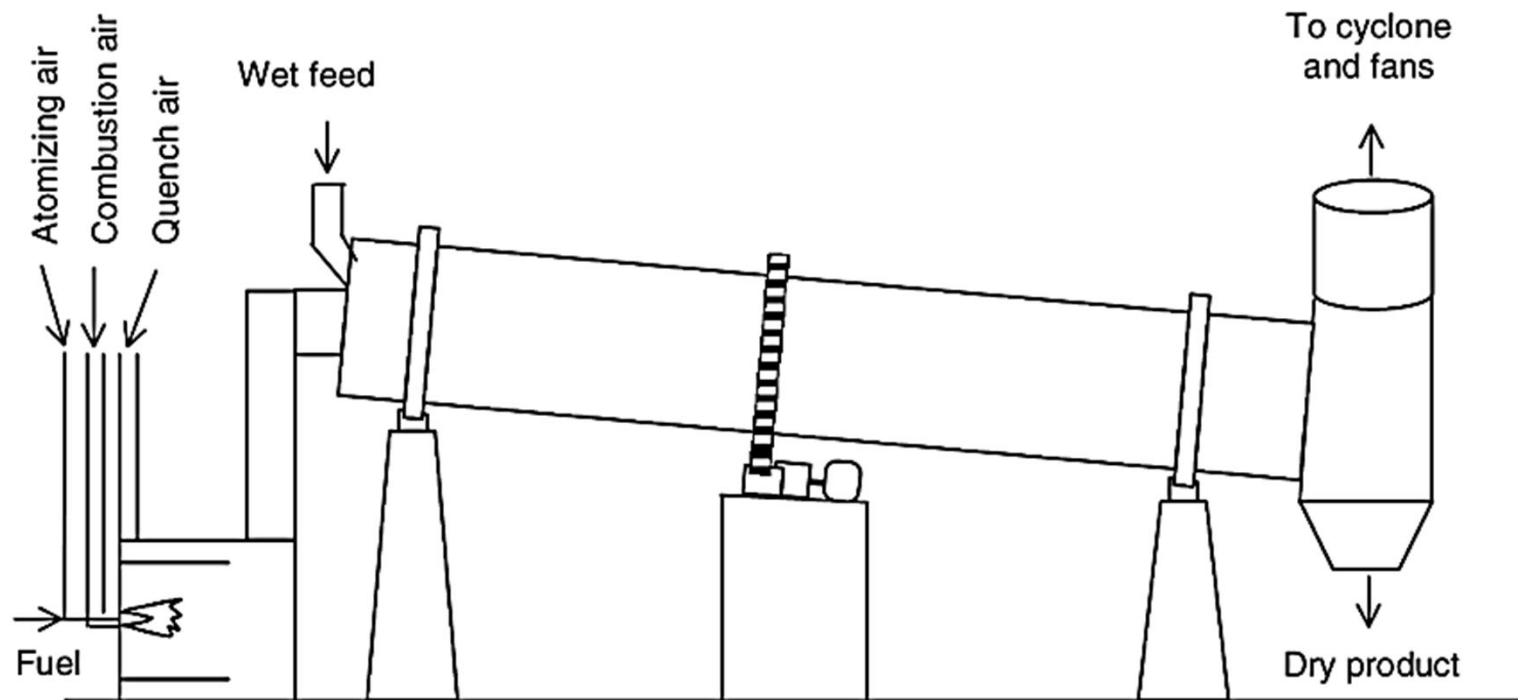


FLUIDIZED BED DRIER

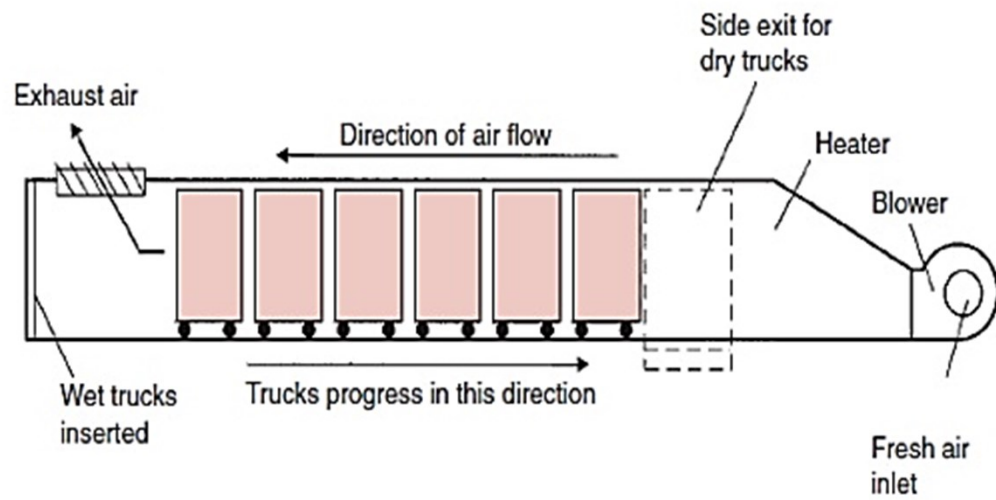
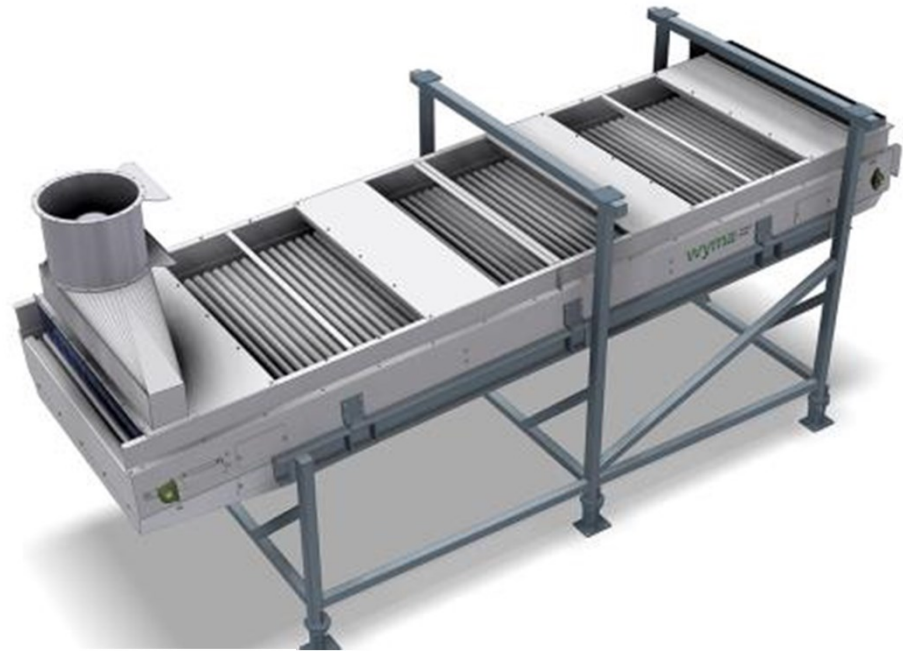
- **Continuous Dryers**



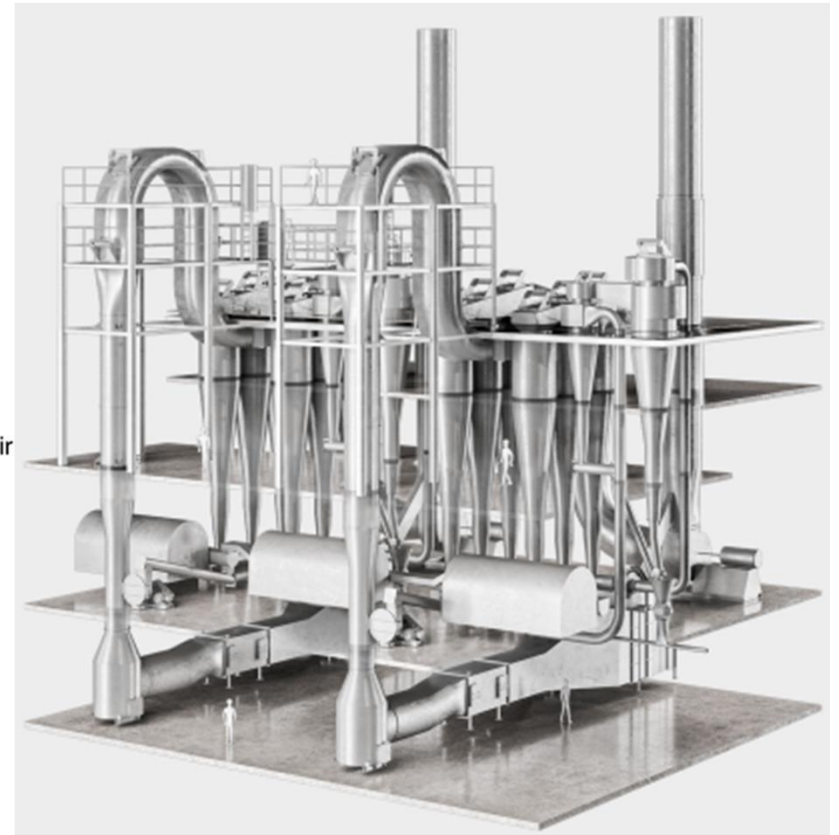
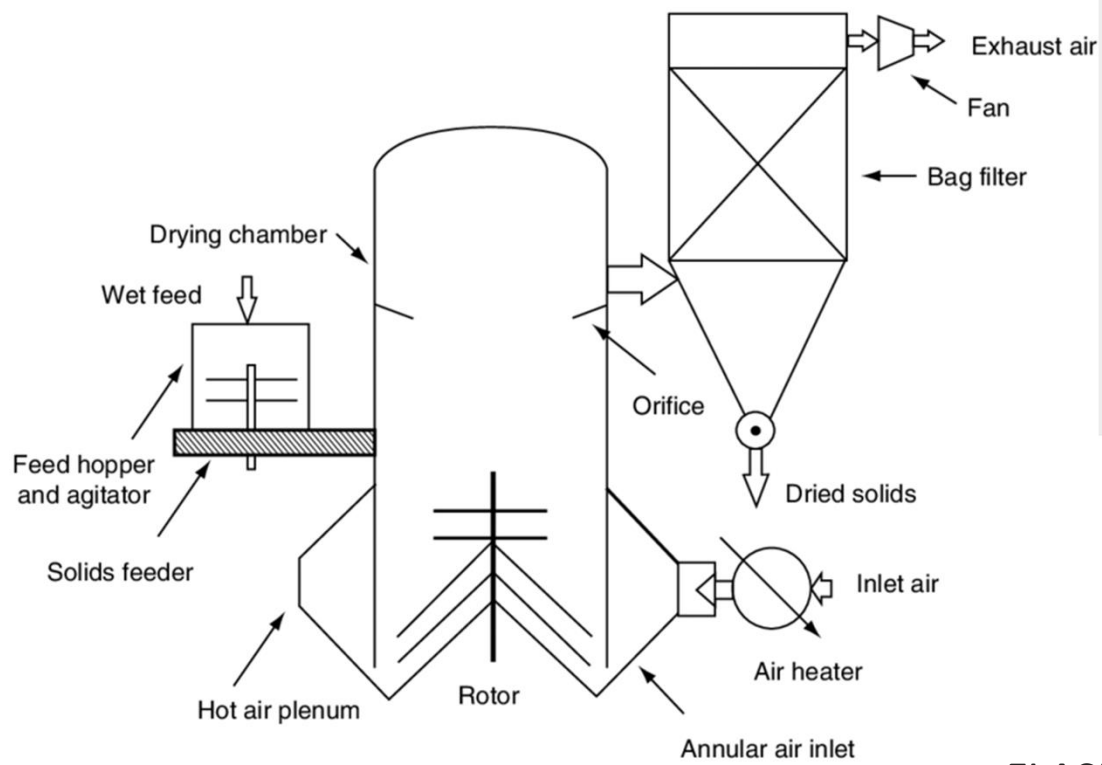
BELT DRYER



ROTARY DRYER



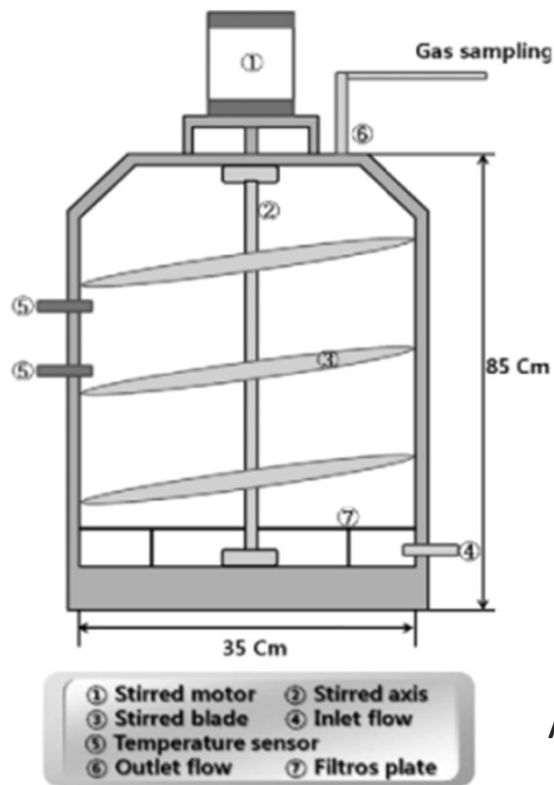
TUNNEL DRYER



FLASH DRYER

Indirect Dryers

- Batch Dryer



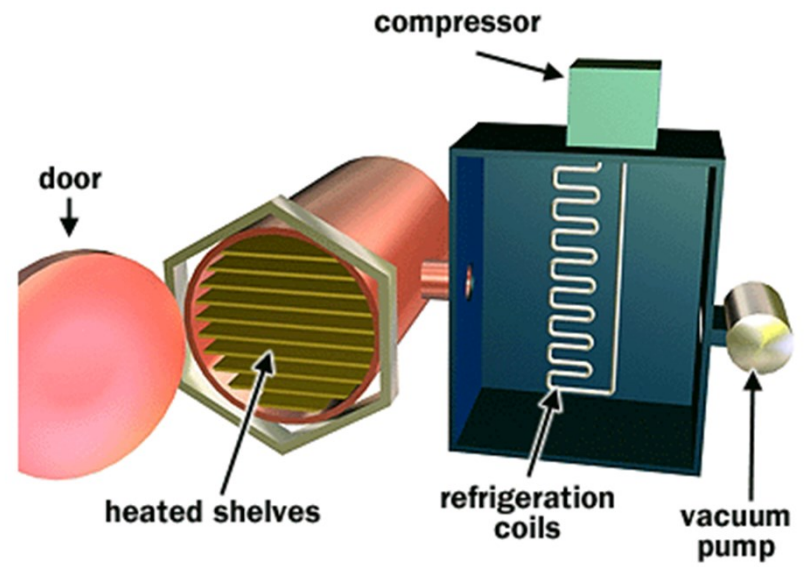
AGITATED PAN DRYER

VACUUM TRAY DRYER

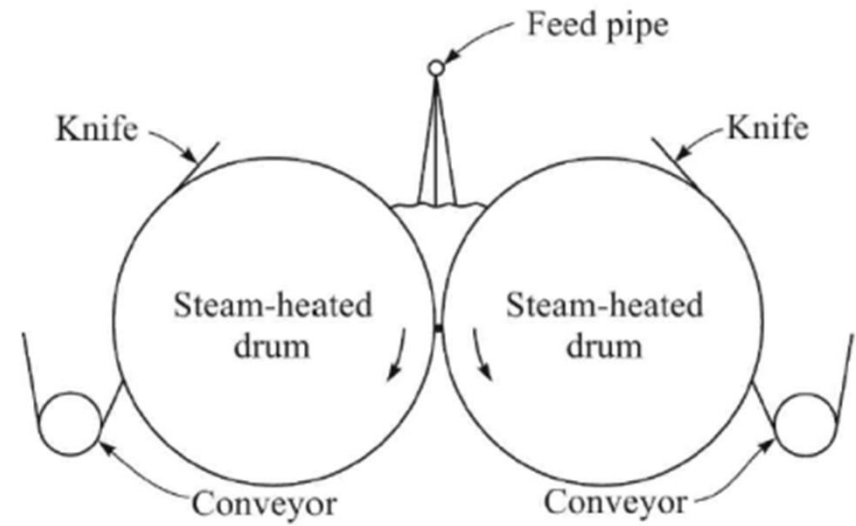
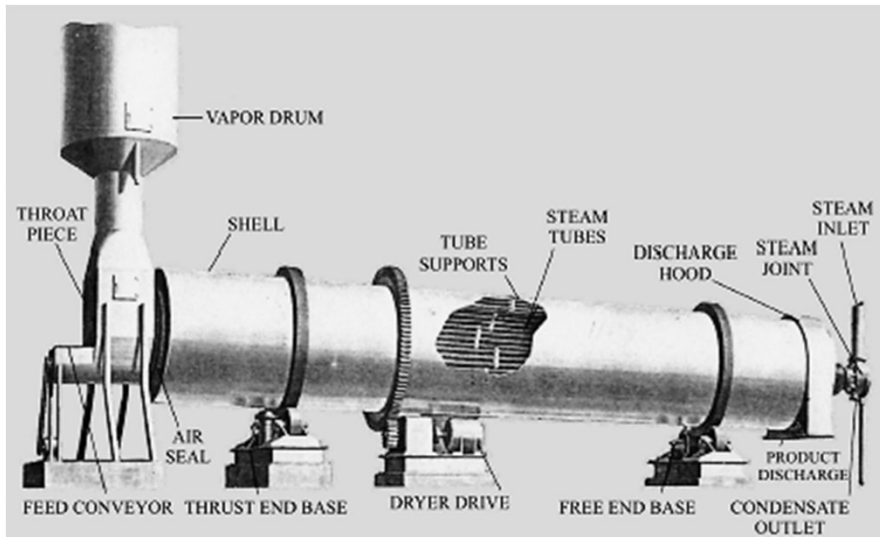




JACKETED SHELF



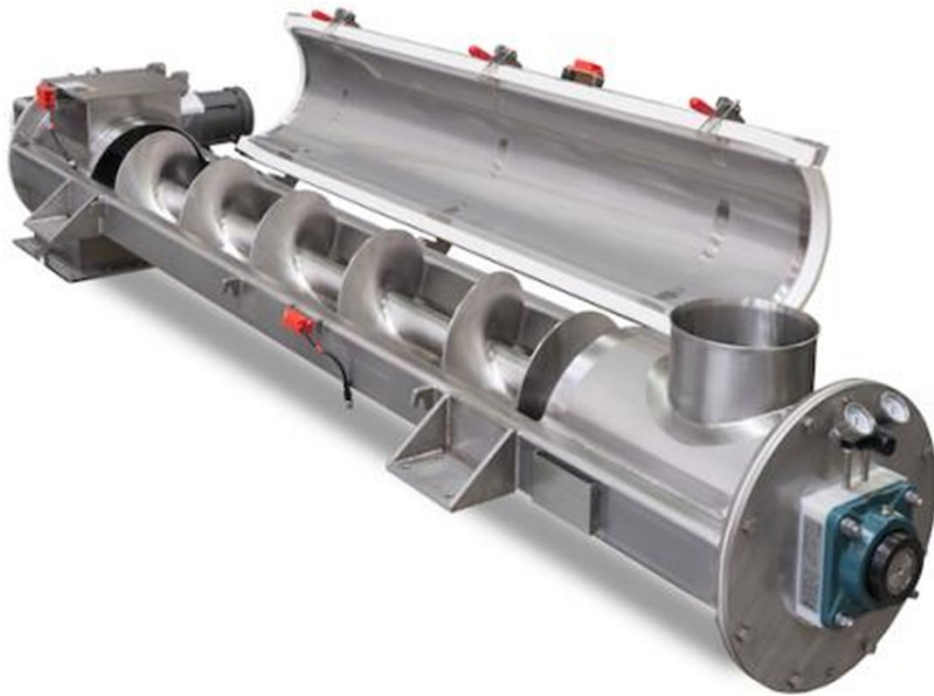
FREEZE DRYER



STEAM TUBE ROTARY DRYER



DRUM DRYER



SCREW CONVEYOR DRYER



TROUGH DRYER

The Mechanism of Batch Drying

The drying process in the constant rate period is known reasonably well, however understanding of the falling rate periods is very limited.

Cross-Circulation Drying

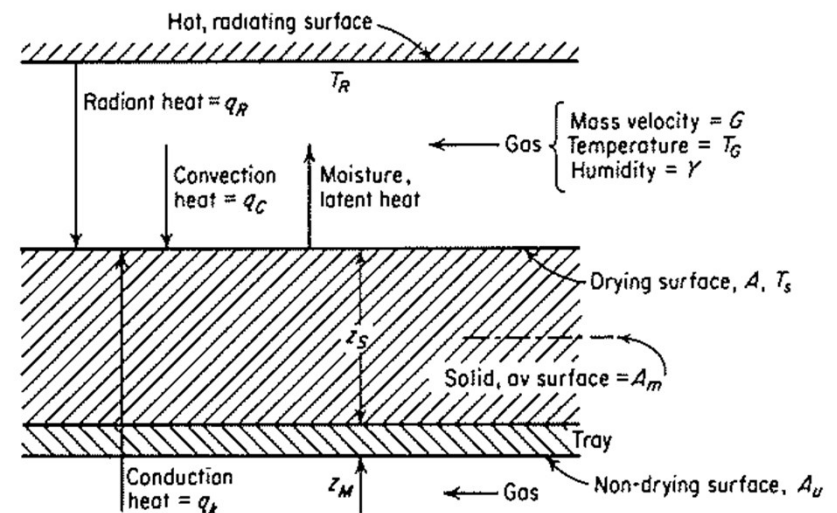
The constant rate period: in this period, where surface evaporation of unbound moisture occurs.

It has been shown that the rate of drying is established by a balance of the heat requirements for evaporation and the rate at which heat reaches the surface.

Consider the section of a material drying in a stream of gas as shown in figure.

The solid of thickness z_s is placed on a tray of thickness z_M .

The whole is immersed in a stream of drying gas at temperature T_G and humidity Y mass moisture/mass dry gas, flowing at a mass velocity G mass/(time)(area)



The evaporation of moisture takes place from the upper surface, area A , which is at a temperature T_s .

The drying surface receives heat from several sources:

- (i) q_c by convection from the gas stream
- (ii) q_k by conduction through the solid
- (iii) q_R by direct radiation from a hot surface at temperature T_R , as shown expressed in flux.

Heat arriving at surface by these methods is removed by the evaporating moisture, so that the surface temperature remains constant at T_s .

The rate of evaporation and the surface temperature can then be obtained by a heat balance. If q represent the total heat arriving at the surface, then

$$q = q_c + q_R + q_k$$

If neglect the heat required to superheat the evaporated moisture to the gas temperature and consider only the latent heat of vaporization λ_s , the flux of evaporation N_c and the flux of heat flow are related

$$N_c \lambda_s = q$$

The heat received at the surface by convection is controlled by the convection heat transfer coefficient h_c .

$$q_c = h_c(T_G - T_s)$$

The heat received by radiation can also be expressed as a heat transfer coefficient h_r

$$q_R = \epsilon(5.729 \times 10^{-8})(T_R^4 - T_s^4) = h_R(T_R - T_s)$$
$$h_R = \frac{\epsilon(5.729 \times 10^{-8})(T_R^4 - T_s^4)}{T_R - T_s}$$

The heat received by convection and conduction through the solid can be computed by heat transfer through a series of resistances

$$q_k = U_k(T_G - T_s)$$

$$U_k = \frac{1}{(1/h_c)(A/A_u) + (z_M/k_M)(A/A_u) + (z_S/k_S)(A/A_m)}$$

h_c is convection coefficient for tray, and A area at thermal resistance at the junction of the drying solid and the tray material.

Combining equations and permit to calculate the rate of drying

$$N_c = \frac{q}{\lambda_s} = \frac{(h_c + U_k)(T_G - T_s) + h_R(T_R - T_s)}{\lambda_s} = k_Y(Y_s - Y)$$

The surface temperature must be known in order to use the relationship. Equation is rearranged to read

$$\frac{(Y_s - Y)\lambda_s}{h_c/k_Y} = \left(1 + \frac{U_k}{h_c}\right)(T_G - T_s) + \frac{h_R}{h_c}(T_R - T_s)$$

The ratio h_c/k_Y applicable to flow of gases past wet bulb thermometers and for the air water vapor this ratio is same as humid heat of the gas C_s .

When unbound moisture is being evaporated both Y_s and T_s can be found by solving above equation with saturated humidity curve on a psychrometric chart.

If conduction through the solid and radiation effects are absent then equation reduce to wet bulb thermometer equation and surface temperature is the wet bulb temperature of the gas.

Drying surface will also be at the wet bulb temperature if the solid is dried from all surface in the absence of radiation.

The transfer coefficient h_c and k_Y are described for different case

- (i) For flow of gas parallel to a surface and confined between parallel plates as between the trays of a tray drier

for $Re = 2600$ to 22000 ,

$$j_H = \frac{h_c}{C_p G} Pr^{2/3} = j_D = \frac{k_Y}{G_S} Sc^{2/3} = 0.11 Re_e^{-0.29}$$

Where $Re = d_e G / \mu$ and d_e is the equivalent diameter of the airflow space.

With the properties of air at $95^\circ C$, this becomes

$$h_c = 5.90 \frac{G^{0.71}}{d_e^{0.29}}$$

For drying of sand in trays h_c was given by

$$h_c = 14.3 G^{0.8}$$

- (ii) Airflow perpendicular to the surface, for $G = 1.08$ to $5.04 \text{ kg/m}^2 \cdot \text{s}$

$$h_c = 24.2 G^{0.37}$$

Parameters affecting drying rate during constant rate drying period

- **Effect of gas velocity**

When radiation and conduction effects are present, the effect of gas rate will be less significant.

However, when they are negligible, then drying rate N_C is proportional to $G^{0.71}$ for parallel flow of gas and to $G^{0.37}$ for perpendicular flow of gas.

- **Effect of gas temperature**

Increased air temperature, T_G increases the driving force, $(T_G - T_S)$ for heat transfer and hence N_C is directly proportional to $(T_G - T_S)$. T_S is at the WBT condition during constant rate drying.

- **Effect of gas humidity**

As the humidity of air decreases, the driving force $(Y_S - Y)$ available for mass transfer increase, and hence N_C is proportional to $(Y_S - Y)$.

- **Effect of thickness of drying solid**

When heat transfer occurs through the solid, N_C increases with decrease in solid thickness. However, if drying occurs from all surfaces, N_C is independent of thickness.

Moisture Movement in Solids

When drying takes place, moisture moves from the inner core to the external surface and evaporates.

The nature of movement influences the drying during the falling rate period and the following theories have been proposed to explain the moisture movement in solids.

- **Liquid Diffusion**

Due to concentration gradients between the higher concentration in depths of the solid and the low concentration at the surface, moisture movement takes place. This type of phenomena is exhibited by substances like soap, glue, gelatin, textiles and paper.

During constant rate period, the rate of moisture movement from inner core and the rate of removal of moisture from the surface balance each other.

However, after sometime, dry spots appear on the surface resulting in unsaturated surface drying and then the moisture movement from the solid takes place which is entirely controlled by the diffusion rates with in the solid.

Whenever, the constant drying rates are very high, the drying substance may exhibit only diffusion controlled falling rate drying shown in figure.

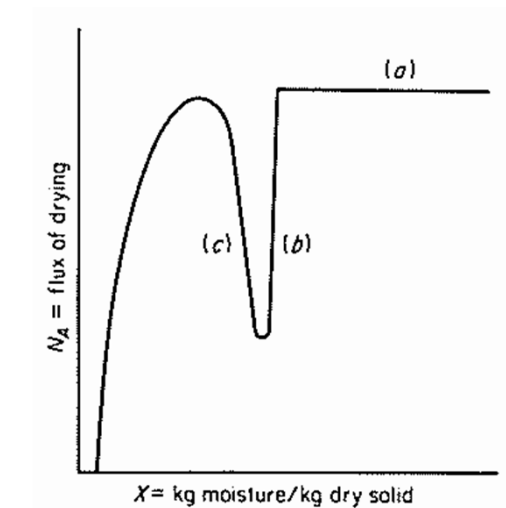
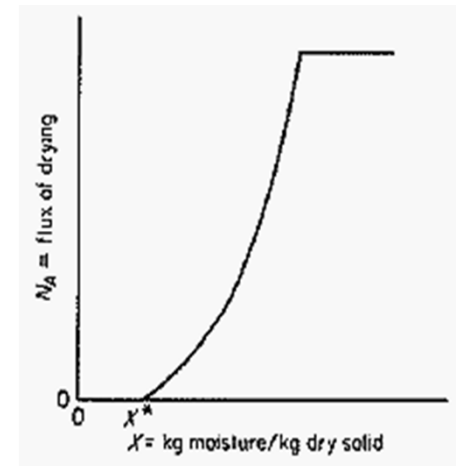
- **Capillary Movement**

In some of the porous solids, moisture moves through the capillaries in them which is quite similar to the burning of lamp with wick. These capillaries extend from water reservoir to the drying surface.

As the drying process is initiated, the moisture starts moving by capillarity to the drying surface and maintains a uniformly wetted surface, which corresponds to constant rate drying period.

Subsequently air replaces the water and the wetted area at the surface also decreases leading to unsaturated surface drying.

After sometimes, when the sub-surface water also dries up, the liquid surface recedes into capillaries and water evaporates from there setting in second falling rate period. This phenomena is exhibited by clay, paints and pigments.



- **Vapor Diffusion**

When one surface of a wet solid is heated and the other surface allows the drying to take place, the moisture gets vaporized from the hot surface and diffuses outward as a vapor from the other surface.

- **Pressure Diffusion**

When bound moisture is removed from colloidal non-porous solid, it tends to shrink when the substance is dried very rapidly.

The moisture present on the surface is removed very quickly and the moisture movement from the inner core to the outer surface will not be equal to the rate of removal of moisture from the surface.

During this process, an impervious membrane forms and prevents the movement of moisture under such circumstances from the inner core to the surface.

The outer surface will be fully dry whereas the inner core will be wet under such conditions. This phenomenon is called **case hardening**.

However, under certain circumstances, the shrinkage of outside layers of solid may also squeeze out moisture to the surface.

Some More Aspects on Falling Rate Drying

The moisture movement during the falling rate period is governed by either unsaturated surface drying or internal diffusion controlling mechanism.

- **Unsaturated Surface Drying**

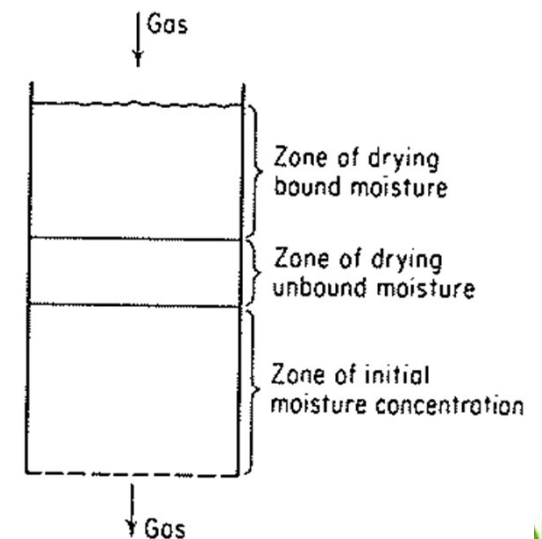
In this phase, the rate of drying will vary linearly with moisture content. The moisture removal mechanism is same as that in the constant rate period and the general effects of temperature, humidity, gas flow rate and thickness of the solid are the same as for constant rate drying.

- **Internal Diffusion Controlling**

In this period of drying, the moisture movement is controlled by the pores in the drying substance. The drying rate decreases with decrease in moisture content.

Through circulation drying

When a gas passes through a bed of solids, the drying zone varies as shown in figure.



At the point, where the gas enters, maximum drying occurs and a zone of drying of bound moisture forms. In this zone there is a gradual rise in temperature.

This zone is followed by a zone of drying unbound moisture. The temperature in this zone remain constant and the particles are at their wet bulb temperature.

The zone of drying unbound moisture is followed by a zone of initial moisture concentration where the solids also remain at their initial temperature. The gas leaves the system fully saturated.

The rate of drying of unbound moisture

Consider a bed of uniform cross section shown in figure, fed with a gas of humidity Y_1 at the rate of G_S mass dry gas / (area bed cross-section)(time). The maximum rate of drying N_{\max} will occur if the gas leaving the bed is saturated at the adiabatic saturation temperature with humidity Y_{as} .

$$N_{\max} = G_S(Y_{as} - Y_1)$$

Where N is expressed as mass moisture evaporated/(area bed cross section)(time). In general, the gas leave the bed at humidity Y_2 , and the instantaneous rate of drying is

$$N = G_S(Y_2 - Y_1)$$

For a differential section of the bed where the gas undergoes a change in humidity dY and leaves at a humidity Y , the rate of drying is

$$dN = G_S dY = k_Y dS (Y_{as} - Y)$$

Where S is the interfacial surface per unit area of bed cross-section. Letting a represent the interfacial surface per unit volume of bed whose thickness is z_S , we get

$$dS = a dz_S$$

And equation becomes

$$\int_{Y_1}^{Y_2} \frac{dY}{Y_{as} - Y} = \int_0^{z_S} \frac{k_Y a dz_S}{G_S}$$

$$\ln \frac{Y_{as} - Y_1}{Y_{as} - Y_2} = N_{tG} = \frac{k_Y a z_S}{G_S}$$

combining equations for rate of drying and above equation will give

$$\frac{N}{N_{\max}} = \frac{Y_2 - Y_1}{Y_{as} - Y_1} = 1 - \frac{Y_{as} - Y_2}{Y_{as} - Y_1} = 1 - e^{-N_{tG}} = 1 - e^{-k_Y a z_S / G_S}$$

This equation provide the rate of drying N if values of $k_Y a$ or N_{tG} is known.

For certain special case $k_y a$ or N_{tG} can be estimated as:

1. Particle small (2.03 to 0.074 mm) with respect to bed depth (greater than 11.4 mm); drying of unbound water from the surface of nonporous particles.

For this case, the constant rate is given by N_{\max} equation and last equation is used for both constant and falling rates, since at high moisture contents the exponential term becomes negligible.

The interfacial surface a varies with moisture content, and it is most convenient to express N_{tG} empirically as

$$N_{tG} = \frac{0.273}{d_p^{0.35}} \left(\frac{d_p G}{\mu} \right)^{0.215} (X \rho_s z_s)^{0.64}$$

Where d_p is the particle diameter and ρ_s the apparent density of the bed, mass dry solid/volume.

2. Particles large (3.2 to 20 mm diameter) in shallow beds (10 to 64 mm thick); drying of unbound moisture from porous or nonporous particles.

During the constant rate period the gas leaves the bed unsaturated, and the constant rate of drying is given by last equation. For this purpose, k_y is given by

$$k_y = \frac{j_D G_s}{Sc^{2/3}}$$